

# Quark Nuggets as Baryonic Dark Matter

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## Abstract

The cosmic first order phase transition from quarks to hadrons, occurring a few microseconds after the Big Bang, would lead to the formation of quark nuggets which would be stable on a cosmological time scale, if the associated baryon number is larger than a critical value. We examine the possibility that these surviving quark nuggets may not only be viable candidates for cold dark matter but even close the universe.

According to the wisdom of the *standard model*, the universe underwent, a few microseconds after the big bang, a phase transition from quarks to hadrons. The cosmological implications of this, *presumably first order*, phase transition would be far-reaching. Schramm and collaborators [1,2] (see also [3]) argued that the associated fluctuations may lead to the formation of primordial black holes, which could be as large as  $M_{\odot}$ , the solar mass, for fluctuations around the horizon scale. They recently suggested [1] that these black holes could even be the candidates for the Massive Compact Halo Objects (MACHO's) [4,5], which had of late been discovered in the halo of the Milky way, in the direction of the Large Magellanic Cloud (LMC) through their gravitational microlensing properties. On the other hand, a first order phase transition scenario involving bubble nucleation at a critical temperature  $T_c \sim 100 - 200$  MeV should lead to the formation of quark nuggets (QN) [6], made of  $u$ ,  $d$  and  $s$  quarks at a density  $\geq$  nuclear density. If these primordial QN's existed till the present epoch, they could be possible candidates for the dark matter [6]. Such a possibility would be aesthetically rather pleasing, as it would not require any exotic physics nor would the success of the primordial (Big Bang) nucleosynthesis scenario be affected [7–10].

The central question in this context then is whether the primordial QN's can be stable on a cosmological time scale. In a recent work [11] using the chromoelectric flux tube model, we have demonstrated that the QN's will survive against baryon evaporation, if the baryon number of the quark matter inside the nugget is larger than  $10^{42}$ . For reasons explained in [11], this estimate is rather conservative. Sumiyoshi and Kajino [12] have estimated that a QN with an initial baryon number  $\sim 10^{39}$  would survive against baryon evaporation. It should be noted at this point that the horizon limit on the baryon number at that primordial epoch is around  $10^{49}$ . The conclusion from these calculations is that the larger primordial QN's within the baryon number window  $10^{39-40} \leq N_B \leq 10^{49}$  are indeed cosmologically stable. (Also noteworthy in this context is the observation that these numbers are sufficiently above the limit ( $N_B \sim 10^{21}$ ) which was obtained by Madsen [10] some time ago, below which the QN's could interfere with the outcome of Big Bang nucleosynthesis.) It is therefore most relevant to ask what fraction of the dark matter could be accounted for by the QN's. The central issue that we wish to address in this letter is whether we can have a scenario where the universe would be closed with QN's of baryon number within the above range. In other words, can the proverbial cosmological dark matter, containing 90% or more of all the matter in the universe, be made up entirely of such QN's ?

It is well known that in a first order phase transition, the quark and the hadron phases co-exist. This configuration would be referred to in the following as the mixed phase. In the quark phase, the universe consists of leptons, photons as well as the quantum chromodynamic (QCD) degrees of freedom (massless quarks, anti-quarks and gluons) and is described by, say, the MIT bag equation of state with an effective degeneracy  $g_Q \approx 51.25$ . Note that the baryon number in this phase is carried entirely by the quarks. The hadronic phase contains baryons, mesons, photons and leptons and is described by an equation of state corresponding to massless particles with an effective degeneracy  $g_H = 17.25$ .

The evolution of the universe in the mixed phase at the critical temperature  $T_c$  of the phase transition is governed by the Einstein equation in the Robertson-Walker spacetime, as described below :

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\epsilon}{3m_{pl}^2} \quad (1)$$

$$\frac{d(\epsilon R^3)}{dt} + P \frac{dR^3}{dt} = 0 \quad (2)$$

where  $\epsilon$  is the energy density,  $P$  the pressure and  $G$  the gravitational constant. Combining eqs. (1) and (2) with the equation of state, we determine the scale factor  $R(t)$  and the volume fraction of the quark matter  $f(t)$  in the mixed phase as

$$R(t)/R(t_i) = \left[ \cos \left( \arctan \sqrt{3r} - \sqrt{\frac{3}{r-1}} (t - t_i)/t_c \right) \right]^{2/3} / \left[ \cos \left( \arctan \sqrt{3r} \right) \right]^{2/3} \quad (3)$$

and

$$f(t) = \frac{1}{3(r-1)} \left[ \tan \left\{ \arctan \sqrt{3r} - \sqrt{\frac{3}{r-1}} \frac{t - t_i}{t_c} \right\} \right]^2 - \frac{1}{r-1} \quad (4)$$

where  $r \equiv g_q/g_h$ ,  $t_c = \sqrt{3m_{pl}^2/8\pi B}$  is the characteristic time scale for the QCD phase transition in the early universe and  $t_i$  is the time when phase transition starts. The bag constant,  $B = (245)^4 \text{ MeV}^4$  in our calculations.

In the mixed phase, the temperature of the universe remains constant at  $T_c$ , the cooling due to expansion being compensated by the liberation of the latent heat. In the usual picture of bubble nucleation in first order phase transitions, hadronic matter starts appearing in the quark matter as individual bubbles. With the progress of time, more and more hadronic bubbles form, coalesce and eventually percolate to form a network of hadronic matter which traps the quark phase into finite domains [13]. The time when the percolation takes place is called the percolation time  $t_p$ , determined by a critical volume fraction  $f_c$ , ( $f_c \equiv f(t_p)$ ) of the quark phase.

Detailed numerical studies on percolating systems yield the result that for bubbles with the same radial size,  $f_c$  is  $\sim 0.3$  [14,15]. We would also use the same value of  $f_c$  here. For the sake of simplicity, we would also assume that the trapped quark domains are all of the same size. (In general, this is not true; there ought to be a distribution of domain sizes. This is an involved problem which we plan to look into in future. The conclusions of this work, however, are not expected to be drastically altered.) From eq.(4), we get  $t_p - t_i = 0.08t_c$ . The values of various time scales in the present case are  $t_c = 46 \mu\text{sec}$  and  $t_p = 27 \mu\text{sec}$ .

In an ideal first order phase transition, the fraction of the high temperature phase decreases from the critical value  $f_c$ , as these domains shrink. For the QCD phase transition, however, these domains should become QN's [6] and as such, we may assume that the lifetime of the mixed phase  $t_f$  (*i.e.*, the time when the cooling due to expansion starts to dominate again and the temperature of the universe starts falling), is  $\sim t_p$ .

The probability of finding a domain of trapped quark matter of co-ordinate radius  $X$  at time  $t_p$  is given by [13],

$$P(z, x_p) = \exp \left[ -\frac{4\pi}{3} v^3 t_c^4 \int_{x_i}^{x_p} dx I(x) (zr(x) + y(x_p, x))^3 \right] \quad (5)$$

where  $z = XR(t_i)/vt_c$ ,  $x = t/t_c$ ,  $r(x) = R(x)/R(x_i)$  and  $I(x)$  is the rate of nucleation per unit volume.  $v$  is the radial growth velocity of the nucleating bubbles, which we left as a parameter.  $y(x_p, x)$  is given by the following equation

$$y(x, x') = \int_{x'}^x r(x'')/r(x'') dx'' \quad (6)$$

Various authors [13,16–18] have proposed different nucleation rates for the cosmic QCD phase transition. Let us start with the prescription of ref. [13], where the nucleation rate is given by the following expression

$$I(t) = r_T \delta(t - t_i) \quad (7)$$

where the prefactor of the thermal nucleation rate  $r_T$  is determined from the requirement  $P(0, t_p) = f_c = 0.3$ , yielding

$$r_T = \frac{3r_c}{4\pi v^3 t_c^4} \frac{1}{y(x_p, x_i)} \quad (8)$$

with  $r_c \sim 1.2$ . This leads to

$$P(z, x_p) = \exp \left[ -r_c \left( \frac{zf(x_i)}{y(x_p, x_i)} + 1 \right)^3 \right] \quad (9)$$

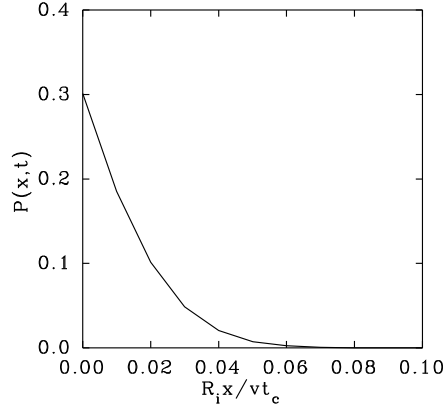


Fig.1: Probability of finding a domain of co-ordinate size  $X$  in the quark phase at time  $t$  as a function of  $R_i X / v t_c$  with the nucleation rate given by eq.(7).

In fig.1, we plot the probability  $P(z, x_p)$  as a function of  $z$ . The radius of the trapped quark domain is determined by the length scale where the probability falls to  $f_c/e$ . This implies

$$\frac{r_{QN}}{v t_c} \approx 0.019 \quad (10)$$

The number density of the QN's ( $n_{QN}$ ) can be obtained by using the relation  $n_{QN} V_{QN} = f_c$  as

$$n_{QN} \approx \frac{1968}{(v t_p)^3} \quad (11)$$

In an idealised situation where the universe is closed by the baryonic dark matter trapped in the QN's, we should have,

$$N_B^H(t_p) = N_B^{QN} n_{QN} V^H(t_p) \quad (12)$$

where  $N_B^H(t_p)$  is the total number of baryon required to close the universe ( $\Omega_B = 1$ ) at  $t_p$ ,  $N_B^{QN}$  is the total number of baryons contained in a single quark nugget and  $V_H(t_p) = 4\pi(ct_p)^3/3$  is the horizon volume.

Demanding that  $v/c \leq 1/\sqrt{3}$ , we get

$$N_B^{QN} \leq 10^{-4.7} N_B^H(t_p) \quad (13)$$

Since the usual baryons constitute only  $\sim 10\%$  of the closure density, a total baryon number of  $10^{50}$  within the horizon at a temperature of  $\sim 100$  MeV would close the universe baryonically. This would require  $N_B^{QN}$  to be  $\leq 10^{45.3}$ , which is within the survivability limit of QN's mentioned earlier.

To study the sensitivity of our results to the nucleation rate, we evaluate the density of QN's for the different nucleation scenarios referred to above.

In the nucleation scenario of Cottingham et al [16] the density of QN's is found to be larger than the previous case  $n_{QN} = 42947/(v t_p)^3$  and the corresponding limit on  $N_B^{QN}$  is given by  $N_B^{QN} = 10^{-6} N_B^H(t_p)$ . For  $N_B^H(t_p) \sim 10^{50}$ ,  $N_B^{QN}$  to be  $\leq 10^{44}$ . Although we have used the exact nucleation rate obtained in eq.(8) of [16], it is straightforward to show that it can also be approximated to a delta function. With the nucleation scenario of refs. [17] and [18],  $N_B^{QN} \leq 10^{44}$  and  $10^{44.5}$  respectively for the value of the surface tension = 50 MeV/fm<sup>2</sup>.

It thus appears that the upper limit on the baryon number of QN's that would close the universe baryonically is not very sensitive to the nucleation mechanism ( little about which is confidently known due to the rudimentary knowledge of the dynamics of the QCD phase transition) and all available estimates point to the real possibility that stable QN's could not only be a possible candidate for cold dark matter but they could even close the universe with total baryon numbers within the window mentioned earlier.

For the sake of completeness, we would like to mention here that QN's with baryon number lower than the survivability window would evaporate rather quickly, leaving a large baryon inhomogeneity. This would still not pose much problem for the cosmological scenario, as this overdensity would dissipate, primarily due to neutrino inflation upto temperatures  $\sim 1$  MeV and then by baryon diffusion, which becomes the dominant mechanism at lower temperatures [19–21]. Even if the initial overdensity due to the evaporating QN's could be as high as  $10^{10-12}$ , it is found to go down by several orders of magnitude by the time nucleosynthesis starts. These details would be reported elsewhere [21].

In order for the stable QN's to be a viable candidate for the cosmological dark matter, they must gravitationally clump, just like normal matter. It may however be asked what, if any, observational signatures could these stable QN's have at the present time. To this end, we may estimate the rate at which such QN's may collide with the earth, in the extreme case where all these QN's were floating around in the universe. For the various scenarios [13,16–18] considered here, the rate of such collisions (density of QN's  $\times$  velocity of QN's ( $v_{QN} \sim 2 \times 10^7$  cm/sec)  $\times$  surface area of the earth ( $\sim 8 \times 10^{17}$  cm<sup>2</sup>)) turns out to be one in  $\sim 10^{15} - 10^{16}$  years for  $v = c/\sqrt{3}$ . The collision rate could be much larger for smaller velocity of the bubble growth as the rate varies as  $1/v^3$ .

More realistically, however, the scenarios proposed here would get substantial experimental support, albeit somewhat indirect, if a sizable flux of stable strangelets ( heavy nuclear objects with very abnormal charge-to-mass ratios ) could be detected in the cosmic rays. We may recall that there has been a report in the literature [22] that such objects may indeed form part of the extragalactic cosmic rays. Extensive plans are under way at this time to look for such objects in high altitude experiments [23,24], the outcome of which would go a long way to shed light on the nature of dark matter.

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